Using Immersive Virtual Environments for Certification

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Abstract

Immersive virtual environments (VEs) technology has matured to the point where it can be utilized as a scientific and engineering problem solving tool. In particular, VEs are starting to be used to design and evaluate safety-critical systems that involve human operators, such as flight and driving simulators, complex machinery training, and emergency rescue strategies. This article describes the unique features of immersive VEs and the issues involved in using them for certification of safety-critical systems.

Keywords: Virtual Reality, Software Certification, Human-Computer Interfaces, Real-Time Simulation.

1. Introduction

1.1. Virtual Environments

A virtual environment (VE) is a computer-generated environment that creates an immersive, multi-sensory, viewer-centered interactive experience [1]. In order to create the illusion of being immersed in a virtual reality, human operators and computer systems are linked through advanced human-computer interfaces that include visual displays, tracking systems, and specialized input and output devices.

VE technology places operators within a three-dimensional world, providing a "natural way" to interact with a simulated reality built from the user's data. The data can be anything that can be represented in a computer: an architectural environment, a model of a human heart, the result of an airflow simulation, an engineering design, an artistic environment, a geographical region, and many other real or imaginary environments. In these environments, a user may, for example, pick up and rotate a virtual object, approach an interesting feature to better inspect it, or fly over a scene to obtain a broader perspective on the system being studied.

Historically, VEs have been associated with an specific display technology: head-mounted displays [2]. However, today's VEs use a variety of displays ranging from enhanced desktop systems to surround screen systems, like the C2 shown in Figure 1. The C2, (similar to the CAVE virtual reality system[3]), is a 12'x9'x12' room where three of the walls and the floor are projection screens. Stereoscopic computer images are projected on these walls based on the position and ori-

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entation of the main user's head. Interaction devices, such as data gloves, wands, and control panels, are used to interact and manipulate the virtual objects and their properties. A localized sound system provides 3D audio capabilities.

Figure 1: C2 surround screen virtual reality display

An interesting feature of surround screen systems is that they allow multiple simultaneous viewers in the system. One user is the active participant controlling the view and interaction, while the rest are passive observers. Another key feature is the natural blend of real objects with virtual objects, as shown in Figure 2.

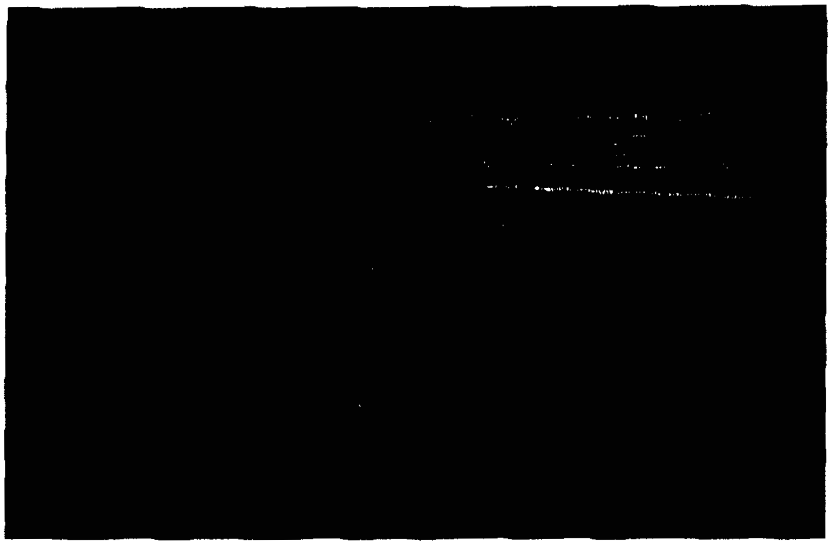

Figure 2: Real and virtual objects blended in the C2

Exploring new worlds, visiting remote places, and investigating computer-simulated spaces via VEs are generating a great deal of excitement and interest in fields ranging from academic research to mass media. Recently, there has been growing interest and investment by industry, where VEs are currently being used to design and test applications involving a broad range of real-world physical phenomena. Many of these applications involve safety-critical aspects: automobile design, space walking practice, surgery training, molecular modeling, historical reconstructions of accidents, and architectural plans for a building [4]. Figure 3 shows an example of a VE to test the safety of a new car design.

Figure 3: VE to test new vehicle features

The use of VEs has the potential to contribute to cost savings in complex systems, to better understanding of customer requirements, and to safer exploration of failure modes, especially in possibly hazardous manufacturing or operational environments. With the advancement of VEs technology, the challenge we face is to learn how to use and apply this technology to provide effective and innovative solutions to long-standing problems.

As VEs move from research laboratories to commercial use, there is a need to define the appropriate role of VEs in certifying the systems they simulate. Certification is sometimes required by regulatory agencies, and other times may be undertaken by the customer for commercial advantages [5]. The rest of this article focuses on the issues involved in using VEs for certification of safety-critical systems with an overview of several applications currently in operation. It concludes with recommended guidelines for the future use of VEs for certification.

1.2. Certification

Broadly speaking, certification is a process whereby a certification authority determines if an applicant provides sufficient evidence concerning the means of production of a candidate product and the characteristics of the candidate product so that the requirements of the certifying authority are fulfilled [6] [7].

Certification of software includes establishing a basis for certification between the certifying authority and the applicant (the developers) that details the applicable regulations, as well as any special conditions, and outlines the means by which the developers expect to demonstrate compliance. The means of compliance are typically specified in standards available from the certification authority. The case for certification involves documenting all relevant aspects of the development process and providing the results of testing and other verification techniques [7].

1.3. Virtual Environments and Certification for safety-critical systems

VEs are designed to stimulate the human perceptual system to create the illusion of being in a computer simulated reality. These environments do not provide an exact match with the physical characteristics of the real world due to technological limitations.The resulting discrepancies between the two worlds can have significant effects upon human perception and performance during an immersive experience [8]. These effects can range from eye strain, dizziness, and nausea to more severe conditions such as disorientation, loss of balance, and loss of consciousness.

An example of how virtual reality design tools can affect the safety of a system is the use of a VE to design a new tractor. Following Leveson [9], safety is defined to be freedom from undesired and unplanned events that result in a specified level of loss. An essential safety feature of the tractor's cab is to provide good visibility to the driver so he can see obstacles both ahead and behind. A prototype of a new tractor cab was developed in a VE and tested on users. While driving the virtual tractor users noticed that one of the head lamps was obstructing the driver's line sight on the left side of the cab. Maneuvers that required a clear view on that side could not be safely performed. A change to the design remedied the situation and was tested successfully in the virtual reality laboratory.

Another example of a safety-critical application is the use of VE for the interactive design and evaluation of new panel displays in airplane cockpits. Currently design techniques involve the construction of physical cockpits. This limits the number of designs that can be tested, since each tested design has significant impact on the overall cost of developing a new airplane. VEs have the potential to reduce the time and cost of prototype evaluation of new displays and cockpit arrangement. This allows the testing of new configurations that can result in safer access to the controls under emergency situations.

Certification and VEs for safety-critical systems need to be examined at three levels: First, immersive environments require certification as a design tool acceptable in the development of critical systems. Certification of VEs involves demonstrational that they meet the domain-specific features and constraints. For example, a VE for vehicle dynamics simulation needs to be validated to ensure the calculations yield appropriate vehicle behavior [10]. In this regard, the certification of a virtual environment can be guided by the tool qualification and certification processes applied to other design tools for critical applications [11][12].

At a second level, the impact of VEs on the human perceptual and motor system needs to be evaluated and measured. Currently, there is an increasing number of research groups dedicated to studying the usability of VEs and their effects on human operators. These studies in principle could be thought of as an extension of studies done for traditional flight and driving simulators. However, this is not the case, because in these simulators the "action" is centered on the vehicle or plane, while in a VE, the "action" is centered on the human operator involving his or her physio- and psychological capabilities. This fundamental difference is the basis for the need to certify

VEs. Humans adapt to the physical characteristics of the world through their perceptual system. One major concern is the neural adaptation to VEs users experience, with the consequent "de-adaptation" to the physical world. Users may be altering their neural structures as they learn to interact with computer-generated worlds, and going through cycles of re-adaptation between real and virtual spaces. At the present, although experiments are under way, there is no data on any of these effects to guide certification measurements [13].

The third, and most intriguing, use of VEs is in certifying systems. Much as piloted simulation is used in the certification of aircraft systems or driving simulators are used in the certification of automobiles, so immersive VEs are beginning to be used for virtual training and operator qualification [14]. Since the requirements for certification vary so much among industries and countries, the use of VEs for certification is necessarily domain-dependent [5]. For example, in the U.S., the process of using VE to certify a flight display will follow FAA rules; the process of using VE to certify a medical application will follow FDA rules, etc. However, some general guidelines drawn from the use of simulations for certification can be stated:

- VEs results can be used to narrow the range of tests required on the actual system for certification
- VEs results can demonstrate compliance with some safety requirements regarding handling of anomalous conditions
- VEs results can be used as part of a safety case to support an application for certification [5]
- VEs results can help certify the limits of safe operation
- Failure scenarios can be run in a VE to demonstrate that the system responds properly in preventing or controlling hazards

2. Challenges

The certification of virtual environments needs to be addressed in a different manner than the certification of more conventional computer development environments. The unique features of VEs described below require special certification criteria and procedures.

- VEs use a variety of visual interfaces ranging from desktop systems to fully immersive projections rooms
- VEs are time-critical systems, requiring response times equivalent to the timing of real world events.
- VEs are "human-in-the-loop" systems, requiring advanced human-computer interaction tools and methods
- VEs are a rapidly evolving technology, with little historical data regarding their usability.
- VEs enable multiple users to share a virtual space, either locally or remotely.

2.1. *Visual interfaces*

The visual displays are one of the most critical components of an immersive virtual environment. Currently, there are five general categories of visual displays: desktop, head-mounted, head-coupled, single projection surface, and surround-screen rooms. Each one of these categories has its advantages and limitations with respect to the others. For example, desktop systems tend to be a low-cost familiar interface, but provide a very limited sense of immersion. On the other hand, a head-mounted display can be highly immersive, but also highly invasive, as it isolates its users from the real surroundings. A surround-screen room provides a non-invasive visual interface to virtual worlds, allowing multiple users to share the space, but requires a large amount of physical space and complex hardware and software tools.

The fact that each display provides a different paradigm to see and interact with virtual worlds and objects suggests the need to have certification criteria dependent at least in part on the specific technology used in the VE.

2.2. *Time-critical environments*

In addition to the visual displays, immersive virtual environments have to integrate a large variety of hardware devices through complex software that must provide a total system performance on the order of a 30th of a second for each input-processing-output cycle. This is usually measured in terms of the frame rate (images per second shown to the user on the visual display) and the latency (the time delay between the input parameters and when the corresponding image appears on the visual display). To achieve a high frame rate and low latency, most VEs software are a collection of small, very optimized multi-threaded or distributed computational components [15]. The testing of the integrated system, to evaluate the proper synchronization and data coherence between all the components, is very challenging, in particular because there are no adequate tools for testing and debugging such environments.

Certification criteria for time-critical environments, although they may have some commonalities with current methods for the certification of real-time systems, will require special metrics to accommodate their efficiency constraints.

2.3. *Human-in-the-loop systems*

VEs are, by their very nature, "human-in-loop" systems, which require sophisticated human-computer interfaces to link the human operator to the computer. As stated earlier, the fact that VE systems are centered on the user raises certification issues regarding how these environments impact the perceptual and motor performance of the users. On one side, extensive data must be collected on the physiological effects of long and repetitive exposure to VEs. On another side, significant research needs to be done in the area of virtual interfaces.

We mentioned earlier that one of the goals of VEs is to provide a "natural" way to interact with computers, but what does "natural" mean? For the past 30 years, we have been successfully interacting with computers using "unnatural" interfaces, such as the keyboard and mouse. Now, we are attempting to replace these tools with natural actions, such as hand motion and voice commands, which are unfamiliar to us in the context of interacting with computers.

To illustrate this phenomenon, we performed the following experiment: an immersive environment for multi dimensional data analysis was developed, based on a very popular desktop tool. Figure 4 shows the original desktop environment and Figure 5 shows our immersive implementation of the same data. We replaced all the mouse interactions to mark, manipulate, and explore the data with hand grasping, finger pointing and walking actions. We then compared the performance of 20 analysts in using the desktop environment and the immersive environment. To our surprise, operators, although more accurate in the spacial perception of the data in the immersive environment, were significantly slower and less functional in interacting with the data. More details can be found at [16].

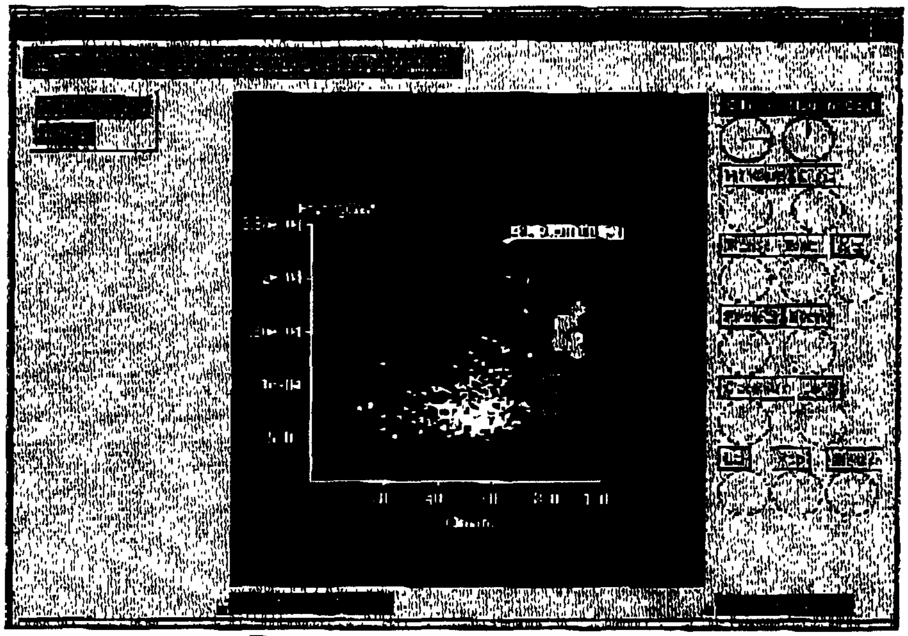

Figure 4: Desktop environment

A more extensive experiment was performed by Disney, as part of the feasibility study for the opening of their new virtual reality theme park Disney Quest. For several years, data of the effects of an entertainment ride using a head-mounted display was obtained by testing it on over 45,000 subjects. The goal of this ride is to fly a magic carpet in the context of the animated Disney film "Aladdin". One interesting finding was that most users had difficulty interacting with the virtual environment, i.e., driving the magic carpet. The authors indicated that users had too many degrees of freedom on the carpet controls, which made hard to maintain the navigation direction and orientation. The results of this experiment can be found at [17].

Based on experiments like the ones just described, certification must rely heavily on empirical evidence from human subjects, both in terms of physiological effects and user-interfaces,. Furthermore, since the penalties of poor performance by a VE can be severe (disorientation and motion sickness) and subjective, a large amount of empirical evidence must be collected to demonstrate compliance with system requirements.

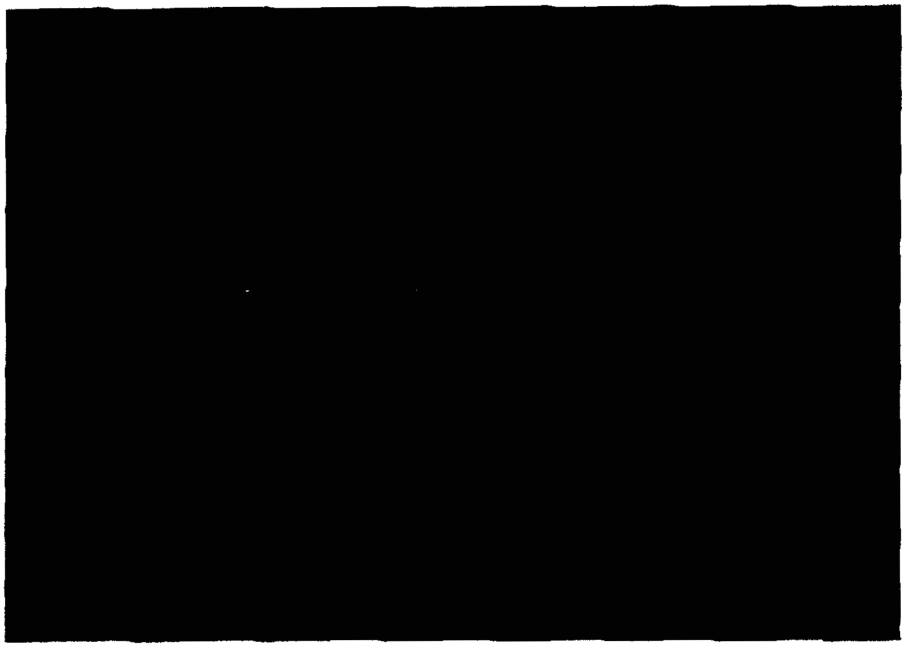

Figure 5: Immersive environment

2.4. *Multi-user environments*

Another aspect of VEs is the possibility of engaging multiple users in the same virtual environment. This can be done in two modalities: several users can share the same visual interface, or several users can share the same virtual space by remotely connecting their individual visual displays via high-speed networks. In addition to the time-critical and human-in-the-loop concerns, multi-user VEs also involve communication and sociological issues that have not yet being fully explored. These issues include methods to transfer control among the users, mechanisms to maintain the data persistency if users disconnect and reconnect at a later time, approaches to deal with time zones (national and international), specifications about the languages allowed on the multi-user environment, techniques to provide visual feedback about the participants, such as video streams, and avatars. There are currently no standards on how to approach any of these issues, which makes certification very challenging.

2.5. *Rapidly evolving technology*

Finally, VE technology, both hardware and software, is evolving very rapidly. Looking back, the first systems appeared in the mid-60s [18], but in the last few years there has been accelerated and on-going developments in virtual reality technology [19]. This means that there is continuous change in devices, interfaces, software tools and applications, complicating collection of historical data about the performance, acceptance, and applicability of this technology.

3. Recommendations

Confidence in a tool's integrity must precede its certification. For VEs this means that as confidence builds in the integrity of particular VEs through additional use, the certification of at least some VEs will be practical. Developers can make a case to the certifying authority for the a specific VE's use as a design tool based on historical data regarding its prior performance in similar applications and based on documentation that the VE's role in the development process is complaint with mandated standards.

Among the factors that a certification of a VE should specify are:

- the experience level of the participants (since an experienced user will have a different learning curve from a novice)
- the level of immersion provided by the VE, determined by the type of visual display used.
- the length of time the user will spend in the VE
- the kind of VE application (e.g., safety-critical, data exploration, or entertainment)
- the interaction devices and methods used
- the maximum and minimum tolerance levels for system latencies, noise and other technology dependent factors.
- what independent authority has evaluated the VE

In order to use a VE for certification of the system itself, the design model of the real world underlying the VE must be validated. For example, it is important that if the model specifies that turning the wheel clockwise will cause a certain shift in the what the driver sees, then that same shift is experienced by a participant in the VE. The VE must thus provide an adequate representation of the physical system being modeled for the purposes of certification.

The validation of the model is commonly achieved in two ways: model analysis and testing. Model analysis evaluates the accuracy of the representation of the VE. Story lists four factors for measuring the quality of simulators that can assist in the model analysis. These are: which environmental variables are included and which are ignored; the accuracy of the representation of the environmental factors; the accuracy and resolution of the calculations used for each environmental variable; and the adequacy of the timing considerations [5].

Testing compares the accuracy of the VE solution with the accuracy of a solution without the immersive environment. The fidelity of the VE can be tested by comparing a participant's actions in the VE with the actions in the actual system being developed [14].

For safety-critical applications, the validation of the VE for use in certification also involves a systematic examination of the design model to ensure that it specifies enough information to verify that the as-built system complies with the safety requirements for the system [20]. In cases where the VE interfaces with actual hardware or software from the system being tested, certification must include evidence that the VE configuration is using the same versions of the hardware and software that will be used in the actual system. In addition, test cases must be designed to separate the effects of the VE (e.g., delays) from the effects of the system being studied.

Human factors certification is grounded in the subjective judgment of experienced users regarding the fidelity of the VE in those features selected for VE-supported certification. However, generalized certification criteria regarding the tolerance limits for human operators to technological flaws, such as system latencies, response lags, and device calibration, need to be specified. Beyond this, tests also validate the users' performance against their performance in the actual systems to be certified. In these tests, the users' actions to control the VE (e.g., applying a brake) and the users' responses to sensory cues (e.g., visual and auditory input) are measured and compared to the designers' expectations.

Certification requires validation of VE results by tests on the actual system. However, the VE can significantly narrow the range of tests required to certify the system. For example, in a complex system there are often many failure modes. VE tests on a system can demonstrate to certification authorities the system's response to a wide range of failure modes. VE tests on a system can also help analyze the severity of the effects and the likelihood of occurrence of failure modes. The failure modes identified as most severe or most likely can then be reproduced in certification tests on the actual system.

4. Conclusions

Virtual Environments are a rapidly developing technology that have an appropriate role in the certification of the systems they describe. VEs provide useful support for the independent evaluation of system compliance against existing standards or guidelines.

Among the advantages of using VEs for certification are the possibility of more complete testing and their dual-use as design tools and as certification tools. This will contribute to increased use of VEs in the certification of safety-critical systems is occurring, especially in analyses of system responses to failure conditions and in testing of hazardous physical conditions.

Additional work is needed in the areas of accumulating a historical database on particular VEs (much like a Product Service History for other tools used in certification), in establishing benchmarks and test case suites to allow comparison of results among VEs, in determining how best to measure the subjective experiences of VE participants, and in separating the effects of VEs from the effects of the systems being tested.

5. Acknowledgments

The authors thank James Bernard and Ricardo Menendez. Images courtesy of the Iowa Center for Emerging Manufacturing Technology at Iowa State University.

Some of the work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by tradename, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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